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THE EFFECT OF ADDITIVES ON FLUID FRICTION

by

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ABSTRACT. A brief review is given of the litera-
ture on turbulent flow of high-polymer solutions.
Laboratory experiments using rotating disks and
turbulent pipe flow have led to generalizations as
to characteristics of friction-reducing high polymers.
Linear, high-molecular-weight, soluble polymers
are shown to be most effective. The maximum drag
reduction achievable by polymer addition appears to
be a function of the Reynolds number of the flow.

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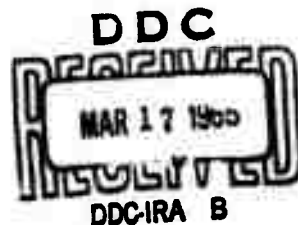
U.S. NAVAL ORDNANCE TEST STATION

China Lake, California

December 1964

FOREWORD

This report is a summary of laboratory experiments in the field of high-polymer solutions undertaken since 1961 at the U. S. Naval Ordnance Test Station.

The work was accomplished under Bureau of Naval Weapons Task Assignment RUTO-3E-000/216-1/R009-01-03, Problem Assignments 401 and 428. Mr. H. A. Eggers was the Bureau of Naval Weapons Project Engineer.

This report is a modified version of a paper presented to the Office of Naval Research Fifth Symposium on Naval Hydrodynamics, 12 September 1964 at Bergen, Norway. The considered opinions of the Propulsion Division and the Hydrodynamics Research Group are presented herein.

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INTRODUCTION

It is now well established that very small concentrations of many natural and synthetic high-polymer substances have the property of reducing the turbulent friction drag of the liquid in which they are suspended or dissolved. Because of the many immediate possible applications of such an effect, current interest is high.

The earliest published data showing turbulent-flow friction reductions in dilute polymer solutions appear to be those of B. A. Toms (Ref. 1), who studied polymethylmethacrylate in chlorobenzene. Flow of "thickened gasoline" was the subject of a U. S. Patent in 1949 (Ref. 2). Work with aqueous solutions of polymers was reported simultaneously by Shaver and Merrill (Ref. 3) and Dodge and Metzner (Ref. 4), all of whom used sodium carboxymethylcellulose as the friction-reducing material. The technique has found commercial use in oil-field applications (Ref. 5 and 6).

Because the earlier workers in the field attributed the friction-reduction phenomenon to "non-Newtonian" fluid properties, the term has become synonymous with the effect. However, the work done at the Naval Ordnance Test Station (NOTS) showed that the turbulent-friction reduction effect can be observed (indeed, becomes most prominent) at polymer concentrations at which the solutions are Newtonian by conventional viscometry. Further, it showed that polymer additives can be effective in reducing the turbulent friction in concentrations of as little as a few weight parts per million (wppm).

Although the exact mechanism of the effect is not known, general rules as to the type of material likely to be effective can be developed, and predictions can be made of the maximum polymer effectiveness in several simple flow situations. The experimental work concentrated on aqueous solutions, but it is believed that the generalizations formulated here apply to all solvent fluids.

EXPERIMENTS WITH ROTATING DISKS

Simply because the apparatus happened to be on hand, early work at NOTS was performed on a large-scale rotating-disk facility. This equipment (Fig. 1) consists of a 3,785-liter water tank in which a 45.7-cm-diameter disk is rotated by a DC electric motor at such a speed that turbulent flow extends over a major portion of the disk. Disk speed and torque are measured by using various concentrations
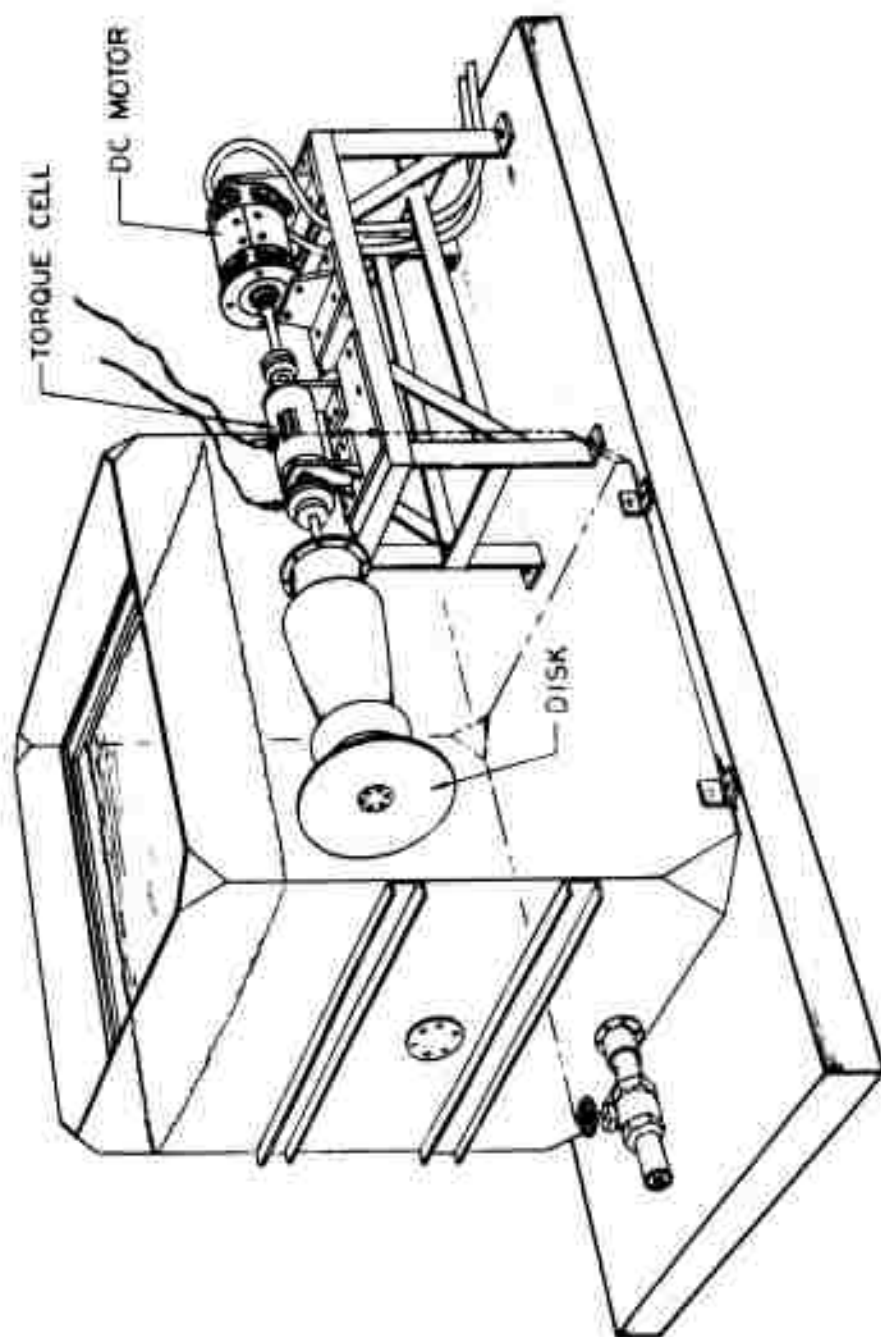
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FIG. 1. Large Rotating-Disk Apparatus.

of polymer additives in the tank. It can be reasoned that most of the torque is developed near the outer disk edge, so that torque reduction is essentially equivalent to friction reduction, and these terms are used interchangeably hereafter.

An example of the type of data obtained with this apparatus is given in Fig. 2. The polymer additive used here is guar gum, the refined endosperm of Cyamopsis tetragonolobus, a plant grown commercially in India, Pakistan, and the United States for food and for industrial purposes.[1] At constant rotative speed, addition of the polymer produces immediate lowering of the torque until, at concentrations of 300 to 400 wppm, the torque has been reduced to between 30 and 40% of its pure water value. As the concentration is further increased, the torque is increased somewhat, a condition that can be attributed to the increased viscosity of the solution.

Much more striking results can be obtained with the use of the synthetic polymer poly(ethylene oxide) commercially available in four different molecular weight distributions.[2] Figure 3 shows data taken with the 45.7-cm-diameter disk at 40 rev/sec for the four molecular weights of the chemical. As molecular weight is increased, the material becomes more effective, and Fig. 3 shows that 70% torque or friction reduction may be obtained with less than 100 wppm of additive, using the material of the highest molecular weight.

Similar tests have been made with a wide variety of natural and synthetic polymers (Table 1). The weight parts per million to achieve a friction reduction of 35% (halfway between no effect and the maximum of about 70% observed on this facility at 40 rev/sec) are listed, together with the molecular weight of the polymer.

From the table, it appears that at least three significant parameters affect the ability of a polymer to lower the turbulent frictional resistance of the fluid in which it is dissolved: linearity, molecular weight, and solubility.

Linearity. The striking thing about the most effective polymers is that they are "long-chain" materials having an essentially unbranched structure. The chemical formulas of guar and poly(ethylene oxide) indicate this characteristic (Fig. 4). A photograph of a model of a segment of the poly(ethylene oxide) molecule further illustrates the threadlike appearance of the material.

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[1] The guar gum used in these experiments was "Westco J-2 FP" supplied by the Western Co., Research Division, 1171 Empire Central, Dallas, Texas.
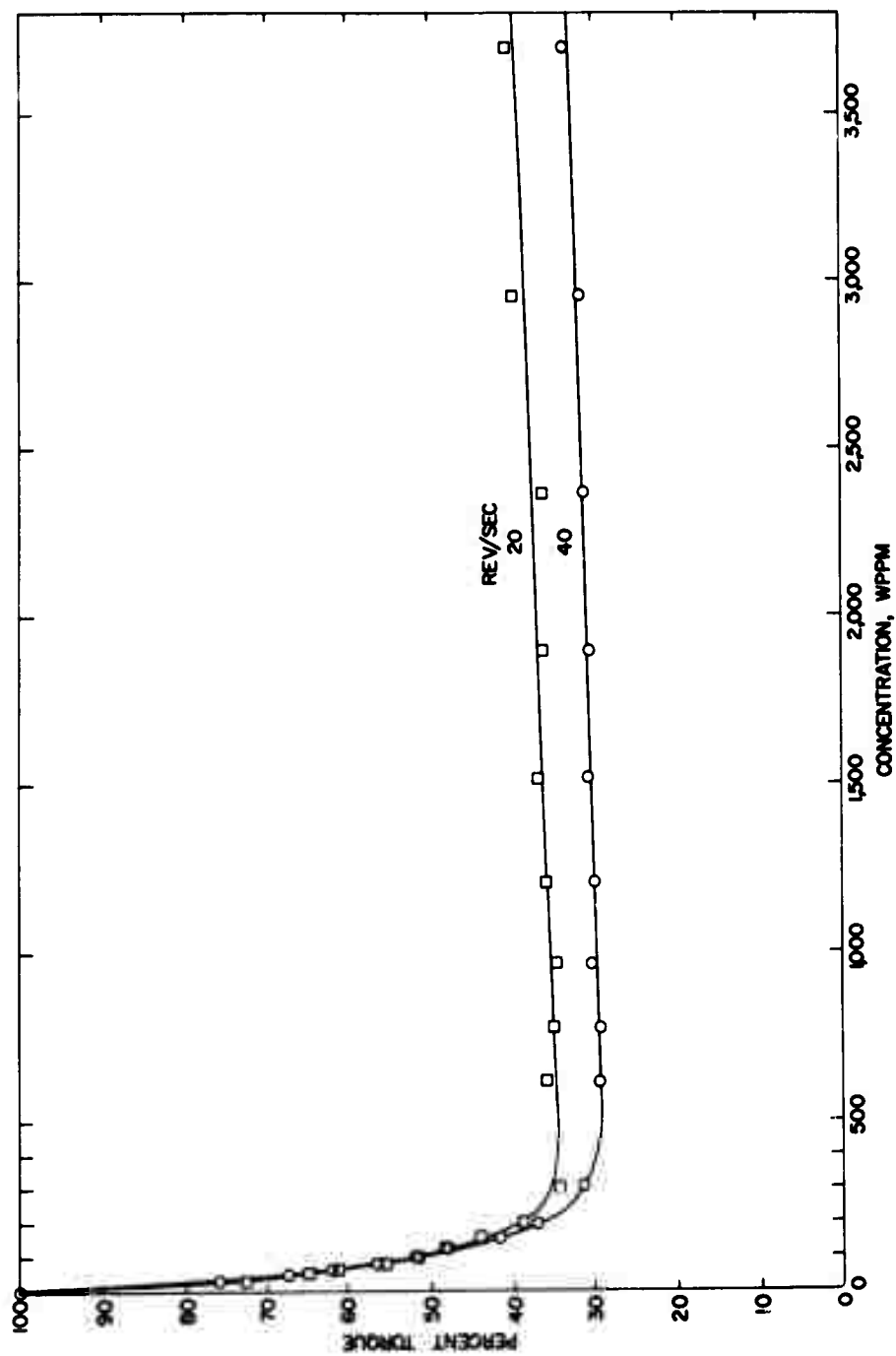[2] Supplied by Union Carbide Corp., 270 Park Ave., New York.

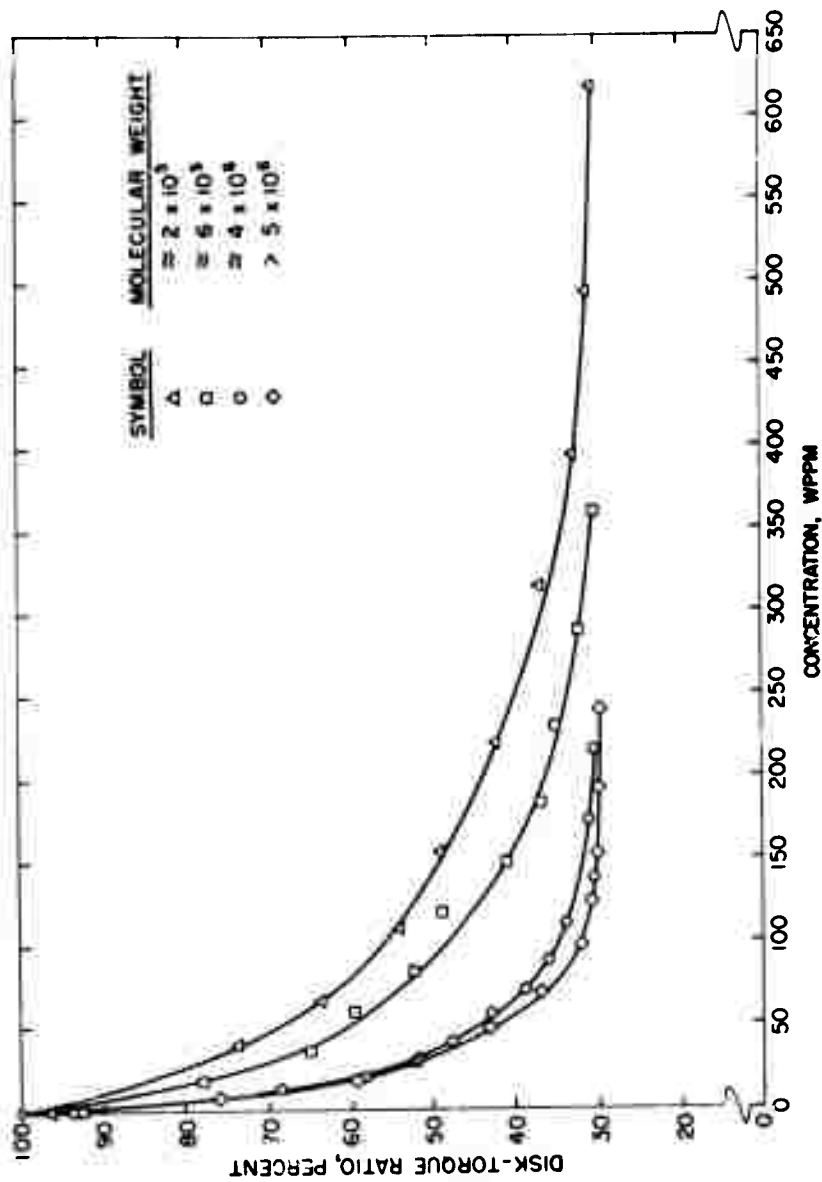FIG. 2. Rotating-Disk Torque Curves for Guar Additive.

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FIG. 3.   Rotating-Disk Torque Curves for Poly(Ethylene Oxide) Additives.

TABLE 1. Comparative Friction-Reduction Effectiveness
of Water-Soluble Polymer Additives Measured
With Rotating-Disk Facility

Additive	C_R [a]	$M \times 10^{-6}$ [b]	Notable Characteristics
Guar gum, w, s (J-2FP) [c]	60	0.2	Straight chain molecule with single-membered side branches
Locust bean gum, m	260 (260) [d]	0.31	Similar to guar but with fewer side branches, causing reduced solubility and less hydrogen bonding
Carrageenan or Irish moss, m (Stamere NK)	650 (420)	0.1 - 0.8	Strongly charged anionic poly-electrolyte
Gum karaya, m	780	9.5	Highly branched molecule; relatively insoluble; acidic
Gum arabic, b	Ineff.	0.24 - 1	Highly branched molecule
Amylose, s (Superlose)	Ineff.	>0.15	Linear chain molecule; retro-grades rapidly
Amylopectin, s (Ramalin G)	Ineff.	1.2	Highly branched molecule
Hydroxyethyl cellulose, u (Cellosize QP-15000) (Cellosize QP-30000) (Cellosize QP-52000)	220 220 160	... ...	Nonionic; formed by addition of ethylene oxide to cellulose; has side branches of various lengths
Sodium carboxymethyl-cellulose, h (CMC 7HSP)	400	0.2 - 0.7	.....
Poly(ethylene oxide), u (Polyox WSR-35) (Polyox WSR-205) (Polyox WSR-301) (Polyox coagulant)	70 44 17 12	0.2 0.6 4 >5	Very water-soluble; no biological oxygen demand; apparently an un-branched molecule with unusual affinity for water
Polyacrylamide, d (Separan NP10) (Separan NP20) (Separan AP30)	26 25 29	1 2 2 - 3	Nonionic Nonionic Anionic
Polyhall-27, s	130	...	.....
Polyvinylpyrrolidone, f (K30) (K90)	Ineff. 2900	0.04 0.36	....
Polyvinyl alcohol, e (Elvanol 51-05) (Elvanol 72-60)	Ineff. Ineff.	0.032 0.17 - 0.22	....
Silicone, u (L-531)	Ineff.	...	.....
Polyacrylic acid, g (Goodrite 773x020 B-3) (Goodrite K-702) (Goodrite K-714)	Ineff. Ineff. Ineff.	0.006 0.090 0.2 - 0.25	....
Carboxy vinyl polymer, g (Carbopol 941)	Ineff.	...	Inconclusive test due to precipitation upon dilution

[a] C_R = concentration required (in weight parts per million) for 35% disk-torque reduction at 40 rev/sec with lake water as the solvent.

[b] M = approximate molecular weight of the polymer according to the literature.

[c] The source of each polymer for this work is indicated by the letter after its name: b = Braun Div., Van Waters and Rogers, Inc.; d = Dow Chemical Co.; e = E. I. Dupont; f = General Aniline and Film Corp.; g = B. F. Goodrich Chemical Co.; h = Hercules Powder Co.; m = Meer Corp.; s = Stein, Hall and Co.; u = Union Carbide Chemicals Co.; w = Westco Research.

[d] C_R values in parenthesis are for solutions given heat treatment to increase polymer solubility.
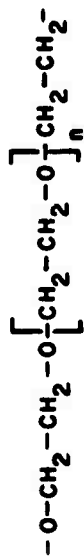
Poly(Ethylene Oxide)
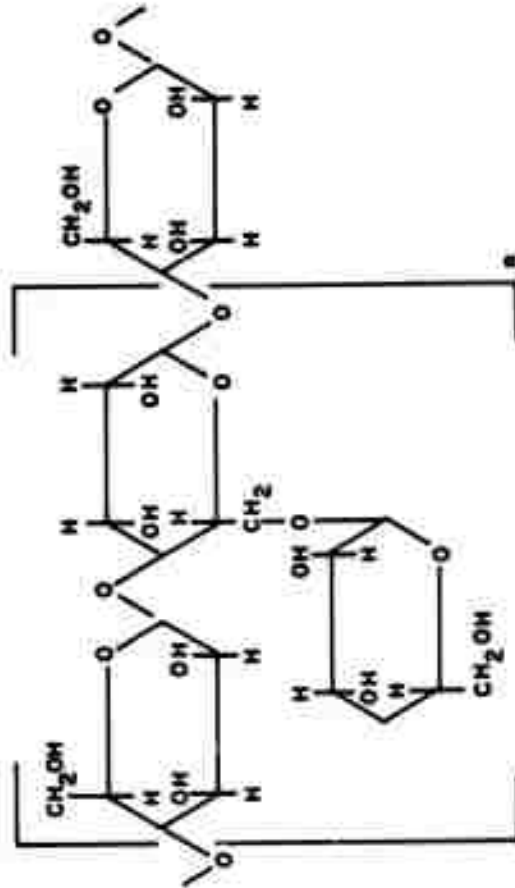
Guar

FIG. 4.   Chemical Formulas of Two Effective Additives.

Although the exact configuration of these molecules in solution is poorly understood, calculations indicate approximate length-to-diameter ratios of from 350 to 500 for guar, and from 22,000 to 165,000 for poly(ethylene oxide) of 6 million molecular weight depending on the helix model selected, if we ignore for the moment the molecular-chain flexibility that will produce a random-coil configuration for such long molecules. Thus the linearity of the molecule appears to play an important role in the drag-reducing effect.

Molecular Weight. Accompanying the linearity is a corresponding increase in molecular weight. However, from the experiments with gum karaya (Table 1), it appears that high molecular weight in itself is not as effective as the linearity. The poly(ethylene oxide) is about 65 times more effective than the heavier gum karaya molecule on a weight basis.

The effect of molecular weight (or linearity) can be demonstrated by replotting the disk data of Fig. 3 taken at a constant rotative speed of 40 rev/sec for poly(ethylene oxide) to give the logarithmic presentation of Fig. 5. In addition to showing the dependence of friction reduction
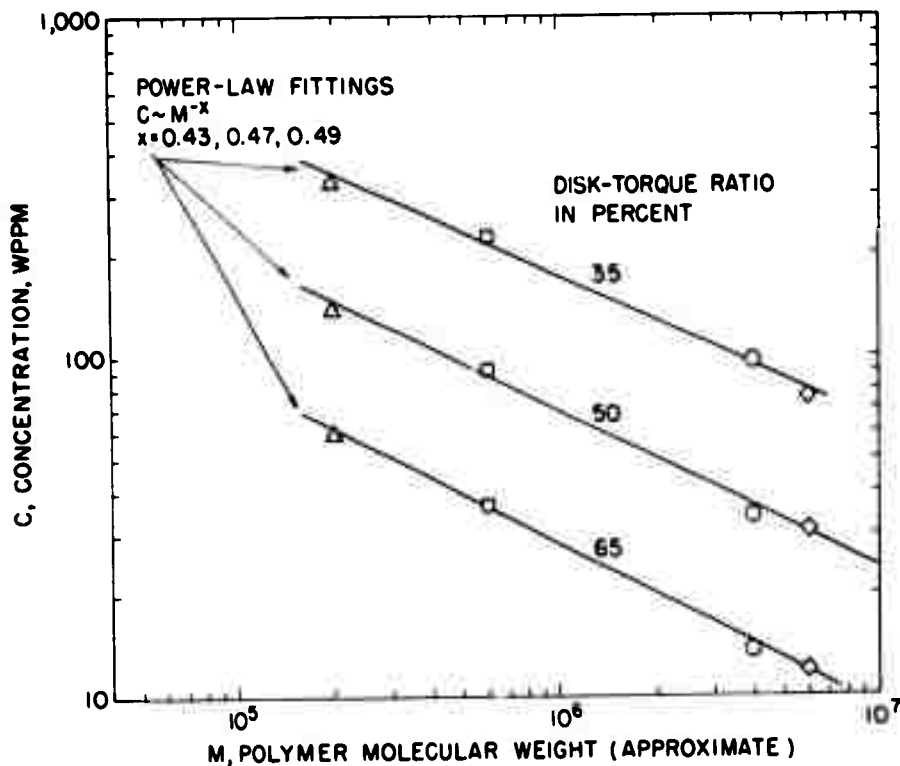

FIG. 5. Dependence of Required Concentrations for Various Disk Torque Ratios on Molecular Weight of Poly(Ethylene Oxide).

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on molecular weight, Fig. 5 also indicates that substantial increases in molecular weight (degree of polymerization) would be required to achieve better friction-reduction performance by, say, an order of magnitude with this particular chemical. Such unusually large macro-molecules would suggest the possibility of finite particles also producing the friction-reduction effect. Experiments with wood pulp (Ref. 7) show that this is indeed the case, but friction reductions were much lower than those reported here. The cause may be related to the third requirement for maximum effectiveness, solubility.

Solubility. Referring again to Table 1, tests with Carrageenan indicate that the greater the solubility the more the friction-reduction effect. Further, molecules such as amylose that otherwise would be expected to be effective do not show up well, probably because of poor solubility.

FURTHER WORK WITH ROTATING DISKS

Because the large-scale rotating-disk apparatus required large amounts of experimental solutions, a smaller apparatus was developed that consisted of a 7.6-cm-diameter disk rotating in two liters of solution. Figure 6 shows experimental data obtained with guar gum in this
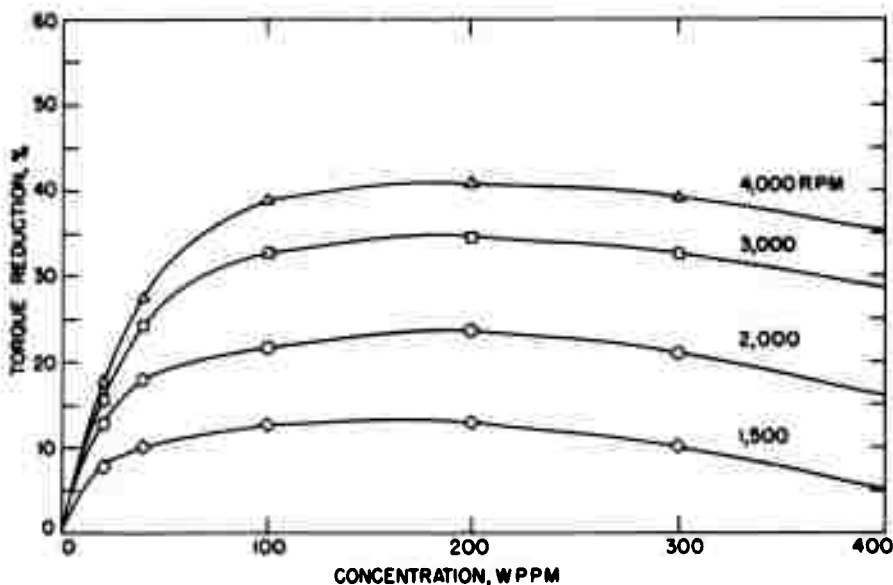

FIG. 6. 7.6-cm Disk Torque Reduction Versus Guar Gum Concentration.

equipment. The maximum torque reduction obtained was on the order of 40%. Similar data are shown in Fig. 7 for solutions of poly(ethylene oxide). The values of the torque reduction obtained with this apparatus as compared to those with the large-scale equipment, together with the variation of torque reduction with rotative speed, suggest plotting these data as a function of Reynolds number.
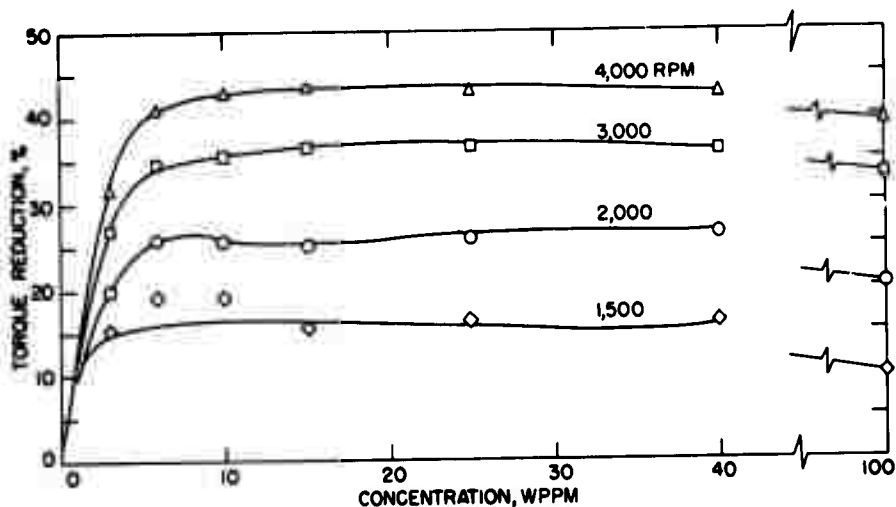

FIG. 7. 7.6-cm Disk Torque Reduction Versus Poly(Ethylene Oxide) Concentration, Mol. Wt. 4×10^6.

Such a comparison is shown in Fig. 8, where data from a 7.6-cm, a 45.7-cm, and a 76.2-cm disk are shown. The resultant envelope of maximum torque reduction obtained in this way seems surprisingly similar for many polymers; that is, the same maximum torque reduction at any given Reynolds number can be obtained with any of the "effective" polymers, with only the concentration required to obtain this reduction varying from polymer to polymer. The Reynolds number used in this plot is based on water viscosity without consideration of any viscosity increase due to the polymer. As some typical data for the maximum torque-reduction curve of Fig. 8, Table 2 lists concentrations of various materials required to attain 70% reduction at a Reynolds number of 1.3 million with the 45.7-cm disk facility.

Effect of Sea Water. The work discussed so far involved the use of tap water or water drawn directly from a fresh-water lake. Additional tests were made with the 45.7-cm rotating disk to show the effect of sea water on the performance of polymer additives. As shown in Fig. 9, friction reduction data taken in simulated sea water agree closely with those obtained for guar with fresh water. The tests were made at
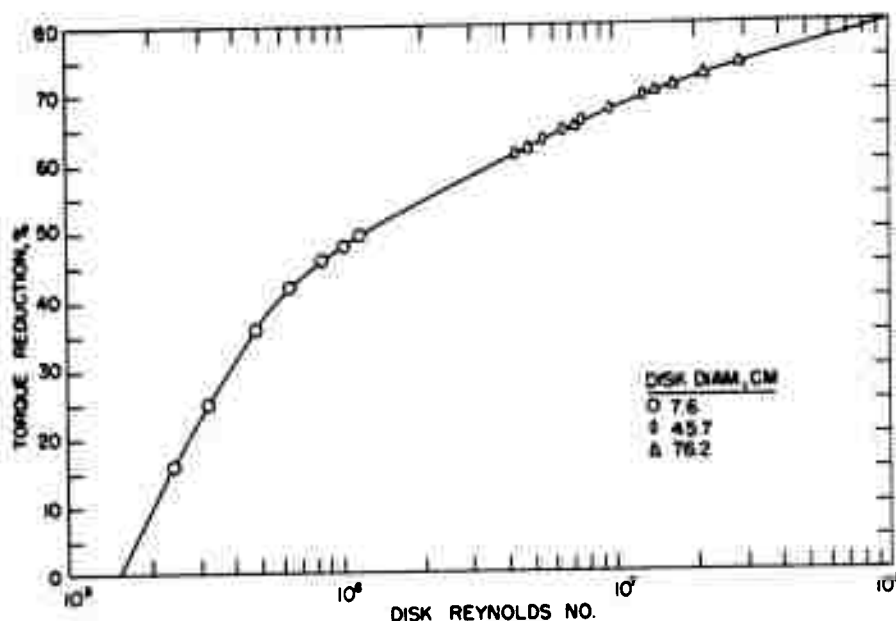
FIG. 8. Maximum Torque Reduction as a Function of Reynolds Number.

TABLE 2. Concentrations (wppm) To Achieve 70% Torque Reduction at a Rotating Disk Re = 1.3×10^6.

See Table 1 for sources and mol. wt.

Guar gum (J-2FP)	500
Locust bean gum	1,700
Gum karaya	2,700
Polyhall-27	850
Polyox-WSR 205	250
Separan AP 30	100

three temperatures ranging from 13°C to 27°C. Poly(ethylene oxide) was shown to be even less affected by the presence of sea-water salts.

Rheological Studies. Since high concentrations (above 1,000 wppm) of these polymers are known to be shear-thinning, early explanations of the friction reduction were based on the "non-Newtonian" (i.e.,
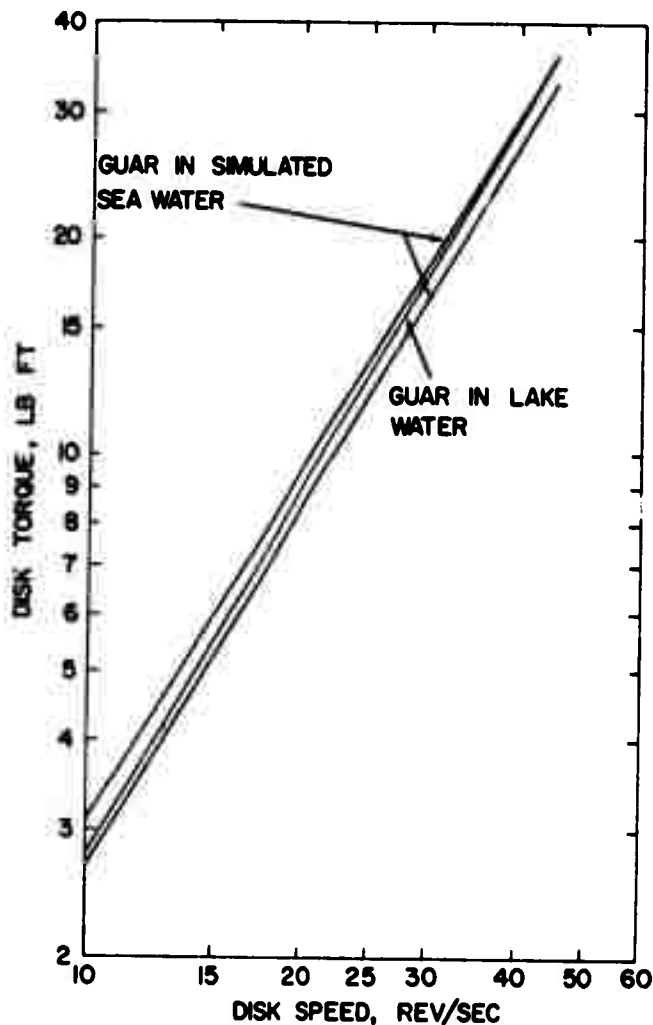
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FIG. 9. Effect of Sea Water on Guar Solution.

variable) viscosity with rate of shear. Considerable effort was for this reason expended upon the rheology of these substances and how their shear-thinning behavior could explain drag reduction.

It was quickly realized, when rheograms were available, that at the concentrations where maximum friction reductions were obtained, these solutions were not "non-Newtonian" but of essentially constant viscosity, greater than that of the solvent. It was only at higher concentrations that departures from constant viscosity were evident. For example, Fig. 10 shows a rheogram for guar, and Fig. 11 for poly(ethylene
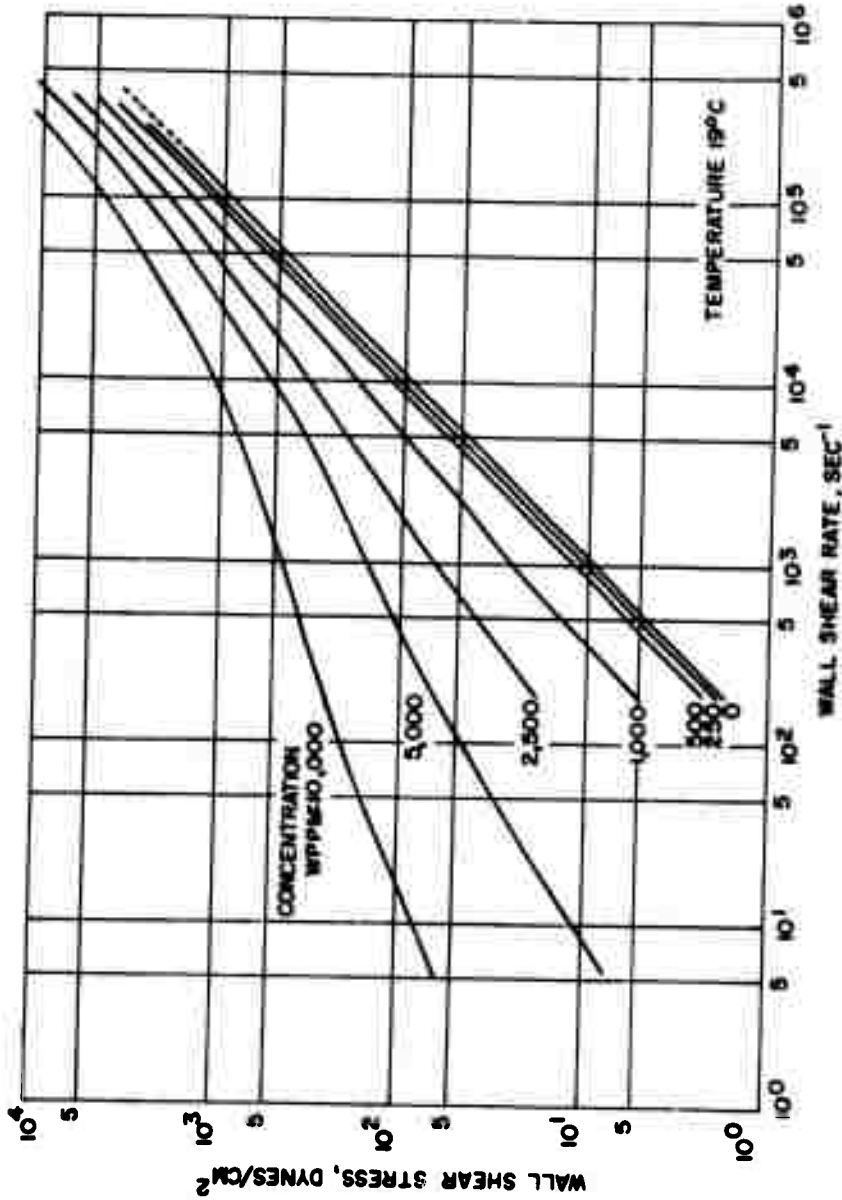
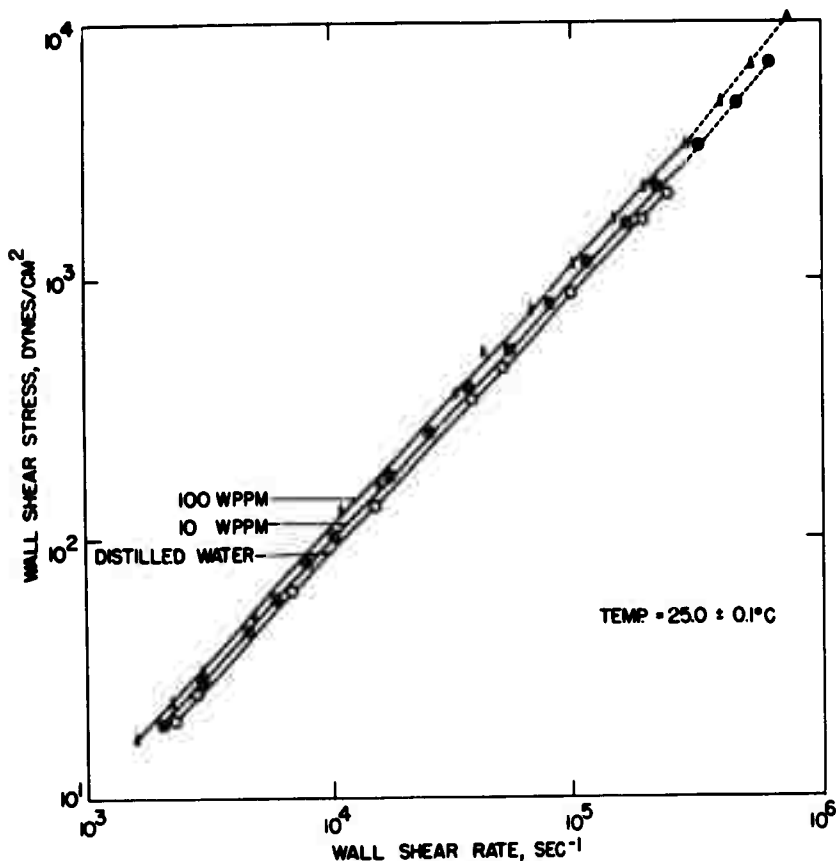FIG. 10. Rheogram for Guar Additive in Water at 19°C.

FIG. 11. Rheogram of Poly(Ethylene Oxide) of 4 Million
Molecular Weight in Water.

oxide) of 4 million molecular weight.[3] At the concentrations of most
interest (under 500 wppm for guar and under 100 wppm for poly(ethyl-
ene oxide), it is difficult, from these data, to ascribe a variable vis-
cosity with shear to these solutions. The constant viscosity extends to
very low shear, as shown in Fig. 12.[4] Thus the term "non-Newtonian"
is inappropriate for these fluids, unless the possibility is considered
that non-steady measurements will show that these solutions display
shear rigidities at high frequencies which ideal "Newtonian" fluids

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[3] These data were obtained under U. S. Navy contract by the West-
ern Co., Research Division, with Fann and Burrel-Severs viscometers.
[4] These data were obtained by J. M. Caraher of this Station with a
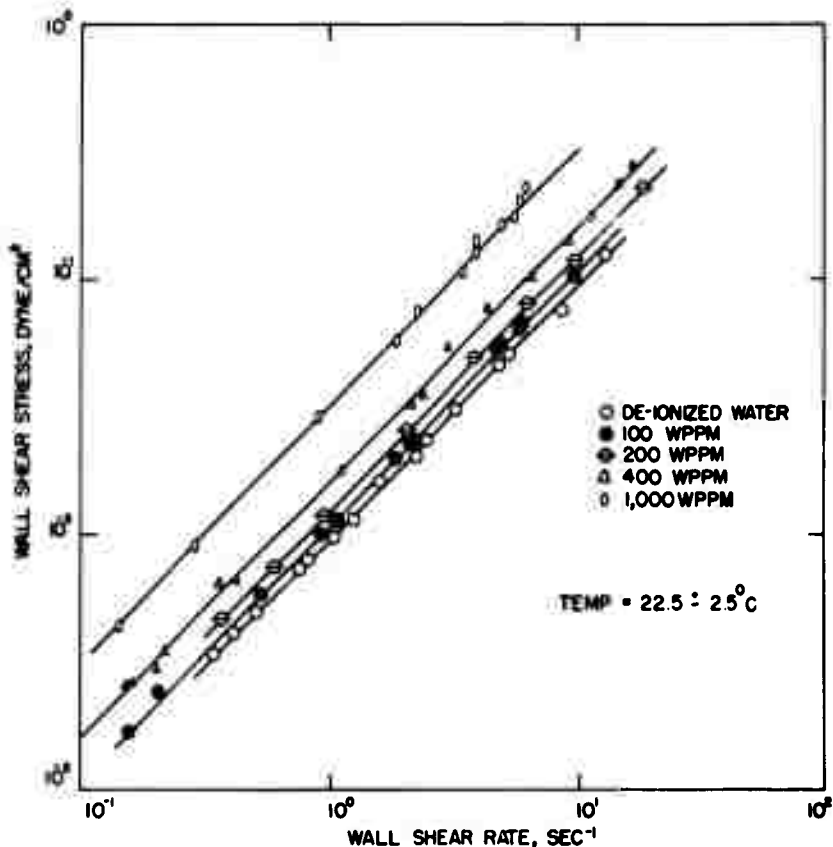new type of helical-coil viscometer of his design.

FIG. 12. Rheogram for Poly(Ethylene Oxide) of 4 Million
Molecular Weight at Low Shear Rates.

would not. J. L. Lumley (Ref. 8) has recently suggested on theoretical
grounds that friction reductions should not be expected from the purely
viscous, non-Newtonian class of fluids. Since many of the effective
additives produce highly viscoelastic solutions in higher concentrations,
it is possible that the drag reduction phenomenon is related to visco-
elasticity. However, viscoelastic solutions are not necessarily effec-
tive drag reducers: e. g., Carbopol (Table 1).

Additional experiments have further shown that the effect is not
enhanced by increasing the viscosity of a solution of guar by "com-
plexing" with sodium borate (Ref. 9). Such a method resulted in lower-
ing the drag-reduction effect based upon the weight of guar in solution.
In a typical test, the addition of sodium borate increased the viscosity
by a factor of 22 over the guar solution alone, and the drag reduction

then obtained was only 70% of that which would have occurred with only guar being used.

In whatever manner the friction is reduced, it seems clear that the action involved is suppression of turbulence intensity. Figure 13
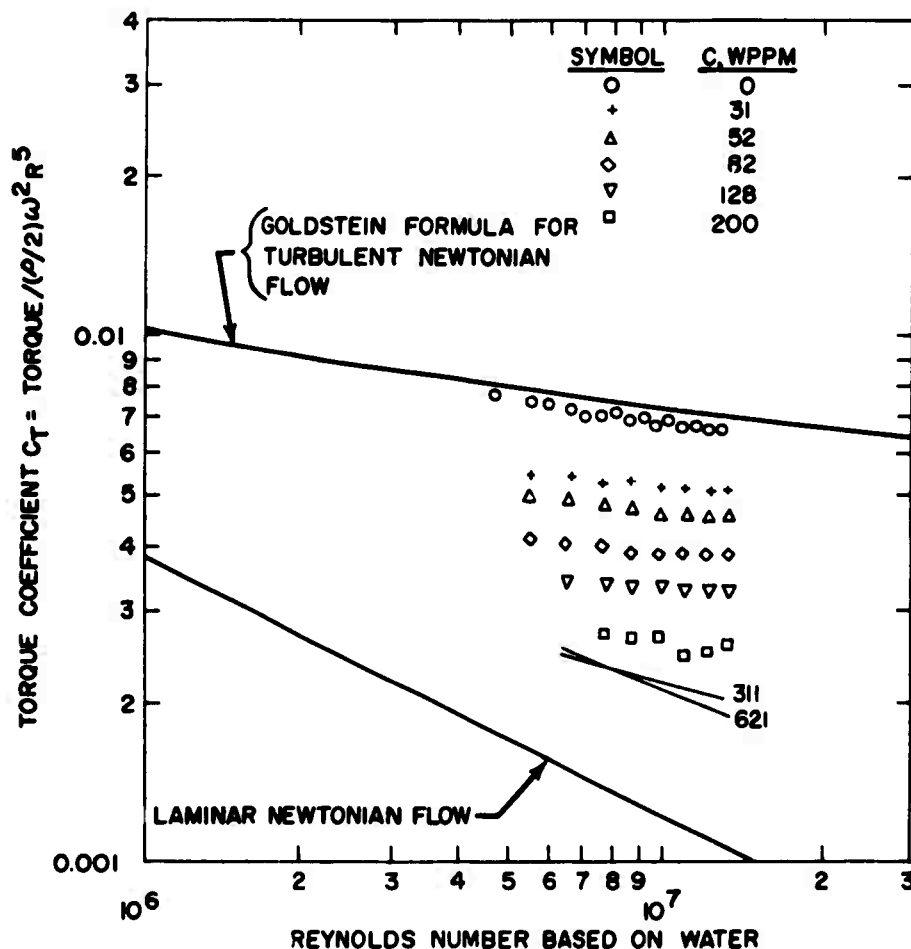

FIG. 13. Torque Coefficient as a Function of Reynolds Number.

shows test data from the 45.7-cm-diameter disk for guar, correlated with disk Reynolds numbers based on water. At concentrations of guar up to 311 wppm, the slopes of the test curves are roughly parallel to, but lower than, the turbulent-flow water data. For 621 wppm and above, the slopes are roughly parallel to, but higher than, the laminar water

flow case. From Fig. 10 it can be seen that no significant changes in Fig. 13 would result from use of Reynolds numbers based on the measured viscosities of the solutions for less than 500 wppm.

PIPE-FLOW EXPERIMENTS

The friction-reducing effect of polymer solutions can easily be studied by measuring the pressure drop occurring in a given length of pipe in which the polymer solution flows. Many experimental facilities of this type have been constructed, and they are in general similar to that shown schematically in Fig. 14, except for the use of air-pressure
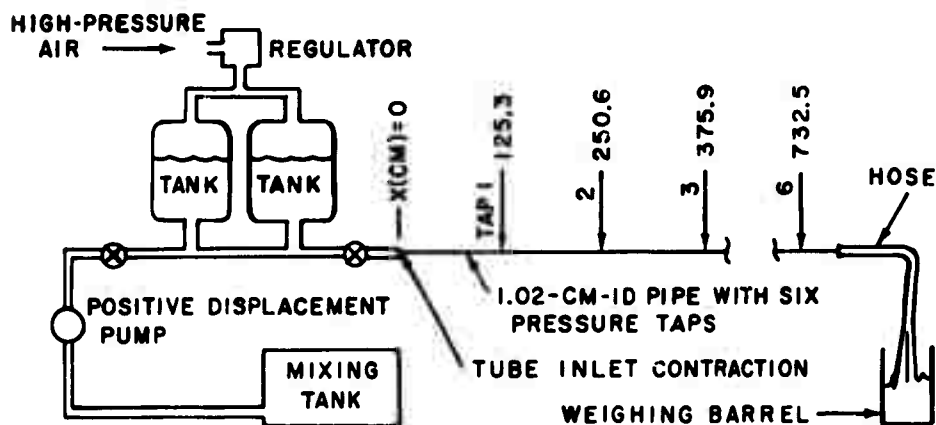

FIG. 14. Schematic Diagram of Blowdown Pipe Apparatus.

pumping to minimize degradation of test solutions (Ref. 10). Pre-mixed polymer solution contained in tanks is forced through the pipe test section where the static-pressure gradient is measured. Flow rates can be determined by weighing the amount of polymer solution discharged in a given time. Discharged solution is discarded to minimize bias due to shear degradation, which occurs very rapidly for many of the solutions. By comparison of similar data taken when pure water was the flowing medium, drag reduction may be calculated.

Typical data using poly(ethylene oxide) of 4 million molecular weight are shown in Fig. 15. Drag reduction of well over 75% is easily obtained. Similar data using the same polymer in sea water but in a different apparatus[5] are given in Fig. 16.

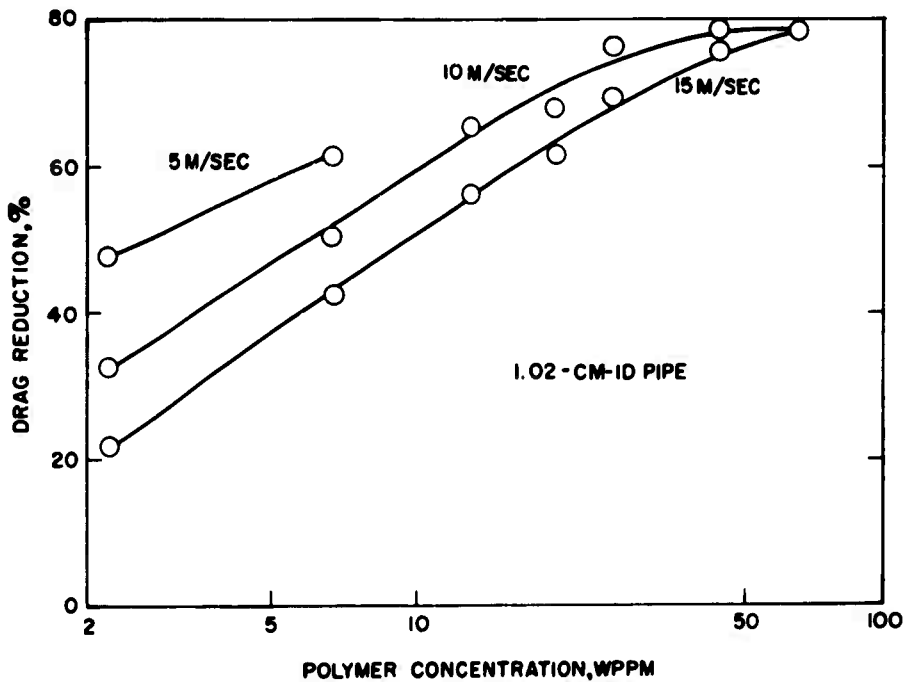[5] Data taken by the Western Co. under U. S. Navy contract.

FIG. 15. Drag Reduction Curves for Poly(Ethylene Oxide)
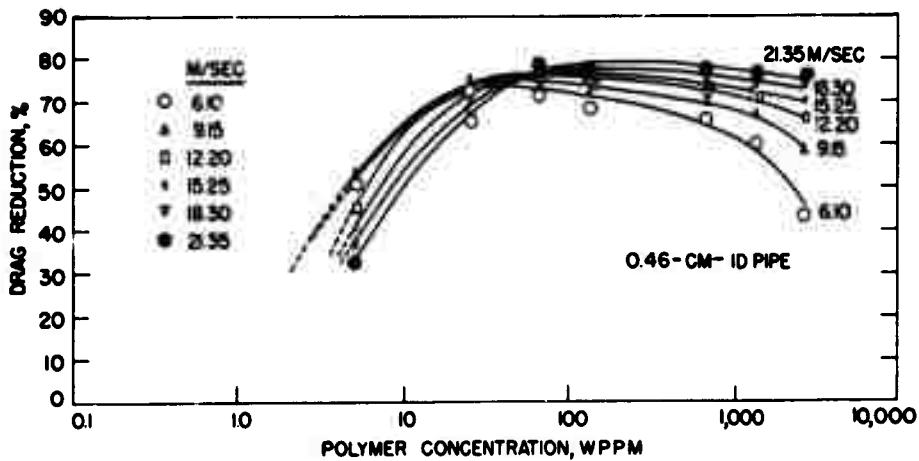in Blowdown Pipe Apparatus.

FIG. 16. Friction Reduction Curves for Poly(Ethylene Oxide)
in Sea Water in Pipe-Flow Apparatus.

Another pipe-flow apparatus, which is essentially a turbulent flow rheometer, has recently been constructed according to the sketch of Fig. 17. The piston of the cylinder is moved upward at 1.245 cm/sec, forcing fluid through the small-diameter pipe. The entire apparatus is mounted vertically to allow entrapped air to escape.

FILLING CUP

PRESSURE TAPS

AUXILIARY, LARGER DIAMETER FILLING PIPE

TEST PIPE 0.109-CM INNER DIAM.

THREE-WAY VALVE

100-CC HYPODERMIC SYRINGE

CONSTANT-SPEED 1/2-HP MOTOR
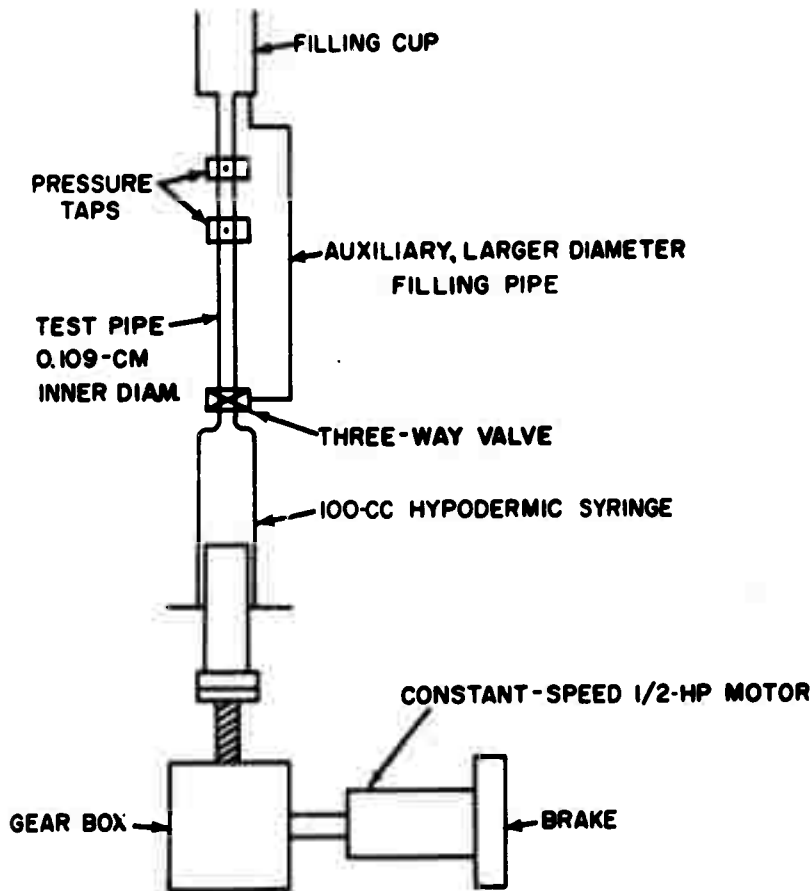
GEAR BOX

BRAKE

FIG. 17. Turbulent-Flow Rheometer.

Some representative data from this instrument, taken at a constant flow velocity of 12.65 meters/sec (Reynolds number based upon water at 21.1°C of approximately 1.4×10^4) are given in Fig. 18.

Data from poly(ethylene oxide) of 4 million molecular weight has been correlated on a pipe-flow Reynolds number basis using the viscosity
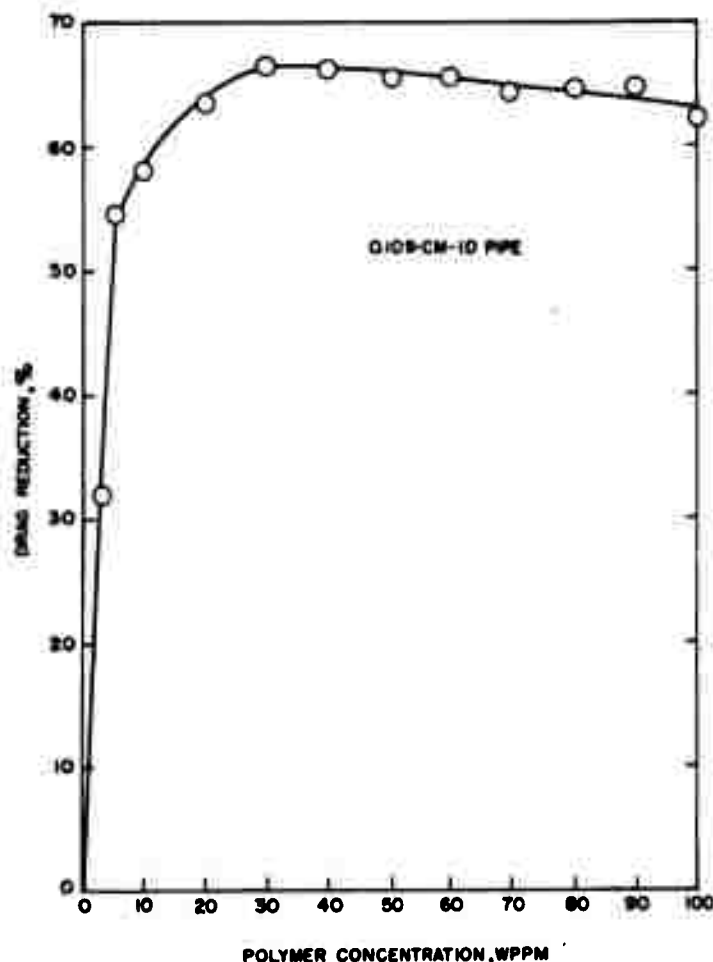
FIG. 18. Turbulent-Flow Rheometer Data for
Poly(Ethylene Oxide).

of pure water. At a concentration of 100 wppm, drag reduction reaches
a maximum of 78-79% at a Reynolds number of about 10^5. At a lower
concentration (30 wppm), the effect falls off at higher Reynolds numbers.
The fall-off may be due to rapid shear degradation of the polymer at the
higher flow velocities.

The envelope of maximum drag reduction shown in Fig. 19 is the
maximum effect obtained for any polymer in pipe flow as a function of
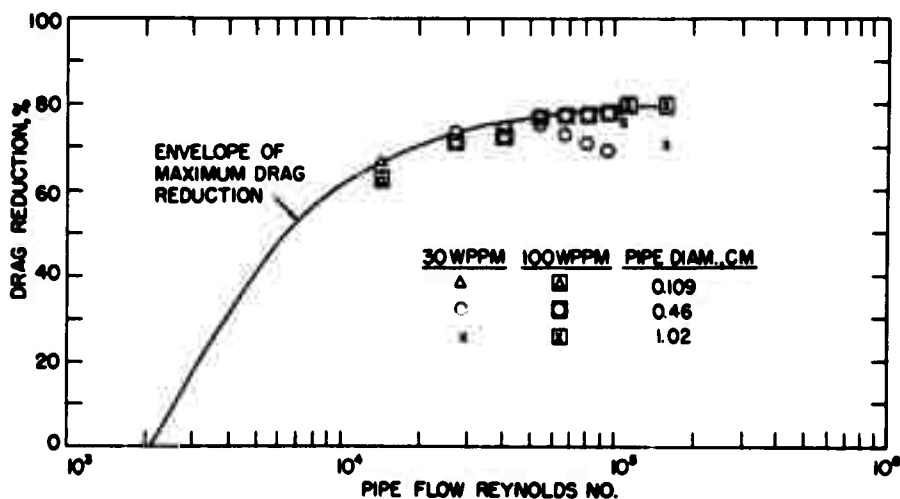Reynolds number. Thus it is an empirical relationship for pipe flow

FIG. 19. Reynolds Number Correlation for Pipe Flow.

corresponding to that given for rotating disks in Fig. 8. These pipe-
flow data are consistent in general with those reported in Ref. 11.

To further demonstrate the validity of Fig. 8, Table 3 lists some
concentrations of materials required to attain the maximum drag re-
duction of 67% at a pipe-flow Reynolds number of 14×10^3.

TABLE 3. Concentrations (wppm) of Material
Required To Achieve 67% Drag Reduction
in Pipe Flow at Re = 14×10^3.

Guar (J-2FP)	400
Colloid HV-6[a] (refined guar)	375
Polyox WSR-301	30
Colloid HV-2[a] (refined guar)	500

[a] Source of polymer: Stein, Hall and Co.
Source of other materials listed in Table 1.

OTHER EXPERIMENTS

The drag-reduction phenomenon has been suggested (Ref. 12) as a possible explanation of certain erratic fluctuations of measured resistance in some towing tanks.[6] Frictional-drag measurements on the same model in the same towing tank are known to be subject to considerable variation, always down from the "standard" and as much as 14%, with no other explanation than that of a "change in resistance characteristics of the water."[7] Since it is known that many algae and marine organisms secrete mucous or slime, it is conceivable that these may act in the same manner as the compounds studied above.

The experiments tallied in Table 4 were not intended to be rigorous or even quantitative, but merely to show the possibility that organic materials similar to those that might be present in towing tanks or other hydrodynamic facilities would affect the measured drag.

From Table 4 it is seen that sizable reductions in drag can be obtained from a variety of natural substances. While concentrations required for significant effect were high enough that the contamination was apparent in these tests, it is conceivable that other, more effective natural contaminants may occur that approach the synthetic polymers in effectiveness at very low concentrations. The search for such contaminants in tank water at the time of drag-reduction excursions must be directed at concentrations of a few parts per million, since 40% friction reduction or more for 2 wppm of high molecular weight polymer is demonstrated in Fig. 15.

It is interesting to speculate on the idea that some marine animals might have evolved the release of friction-reducing agents into their boundary layer. This appears to be a possible area for further research.

APPLICATIONS

The only presently known application of these materials as friction-reducing agents is in oil-field pumping operations. However, the attractive power reductions that seem attainable should promote extensive interest in the further use of these polymers.

In considering applications, however, careful thought must be given to such practical matters as surface roughness, mechanical polymer degradation, and economic feasibility.

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[6] These fluctuations apparently are reduced in tanks where the water is chemically purified.

[7] A comprehensive account of these resistance fluctuation problems is given in "Standard Model Technique at Admiralty Experiment Works, Haslar" by R. N. Newton, ROY INST NAVAL ARCH (LONDON), TRANS, Vol. 102, No. 3 (July 1960), p. 435.

TABLE 4. Drag Reduction of Living Materials

Material	Observed Drag Reduction, %	Apparatus
Algae from fresh water aquarium (principally Ankistodesmus falcatus)	3. 37	7. 6-cm disk
Same with green cells centrifuged out	3. 38	7. 6-cm disk
Green cells resuspended in tap water	0. 45	7. 6-cm disk
Bacteria-free culture of sea diatom Chaetoceros	1. 5	0. 109-cm pipe
Same concentrated to 1/6 volume	14. 5	0. 109-cm pipe
Slime from sea snail in sea water	9. 1	0. 109-cm pipe
Same concentrated to 1/3 volume	12. 0	0. 109-cm pipe
Scraped slime from sea fish in sea water	1. 5	0. 109-cm pipe
Same concentrated to 1/6 volume	14. 5	0. 109-cm pipe

Surface Roughness. A preliminary check on the effect of roughness was made with the large-scale rotating-disk facility. The data shown in Fig. 2, 3, and 5, and in Table 1 were obtained with a smooth, polished disk. Another disk with about 100-microinch-RMS machine-turned roughness was also tested but showed no change in torque required for either water or guar solutions. A rough surface was then produced by means of wrinkle-finish paint. In water tests, the roughness increased the torque at a given speed about 35%. Figure 20 shows that two or three times the concentration of guar gum was required to achieve a given torque reduction with the rough disk. Also, effects of rotative speed appear at low guar concentrations in contrast to the smooth disk data. Nevertheless, it seems clear that the additive can be effective on practical structures.
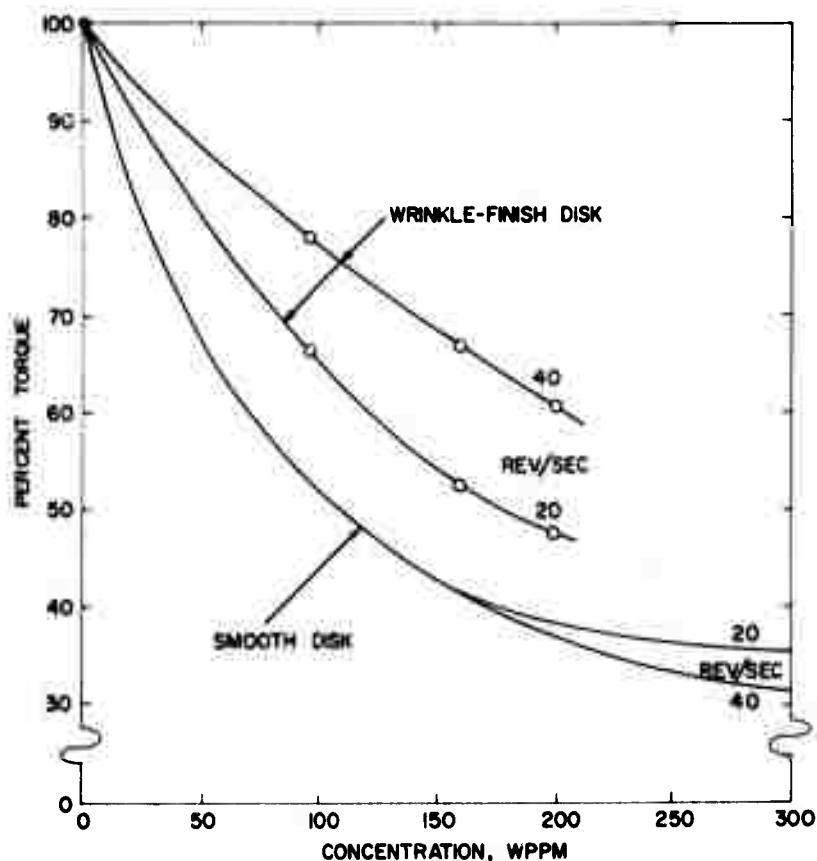
FIG. 20. Effect of High Surface Roughness on the Percent
Torque Reduction With the 45.7-cm Diameter Disk.

Mechanical Degradation. The polymer molecules are subject to
mechanical degradation as the friction-reduction process continues.
For example, concentrations of 15 wppm of poly(ethylene oxide) of
4 million molecular weight were repeatedly tested in the large disk
apparatus, with the results shown in Fig. 21. Each test lasted about
15 seconds and was repeated at intervals of 3 minutes or 10 minutes.
Each test run with this polymer evidently contributed to the mechanical
degradation. A similar test with guar gum did not show this effect, and
for this reason interest continues in this less effective but apparently
very sturdy polymer.

Economic Feasibility. The additive concentrations used in oil-
field applications are about 1,000 wppm and up (Ref. 6). Such concen-
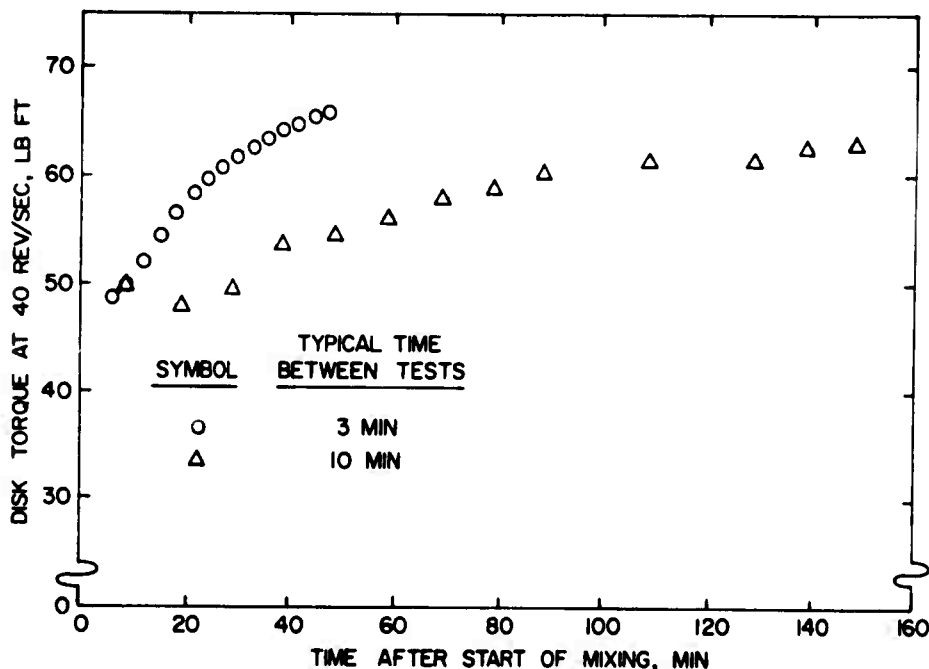trations, if assumed across the full turbulent boundary-layer thickness,

FIG. 21. Rapid Mechanical Degradation of a Dilute Poly(Ethylene Oxide) Solution of 15-wppm Concentration, Seen in Disk Tests.

are out of the question for boundary-layer applications. The reason for this difference in feasible concentrations is simply that the unit of additive in pipe flow is used over and over again until the end of the pipe; whereas, in a vehicle boundary layer, the unit of additive is effective only on a certain wetted surface area for a certain time before it is discarded into the wake.

This key difference can be seen more clearly by comparing fully established pipe flow and high Reynolds number flat-plate boundary-layer flow. A useful measure of performance is

$$\text{Additive effectiveness (A. E.)} = \frac{\text{Power saved}}{\text{Additive weight flow rate}}$$

with units of hp - hr/kg.

In the following, it is assumed that speeds are kept fixed and that only pipe length and plate length are varied.

For pipe flow, assume that an additive weight concentration per unit volume, C, produces a percent pressure drop or friction reduction,

R, for fully established turbulent flow in a pipe of diameter, D, for a throughput of Q, with the mean flow velocity $U = 4Q/\pi D^2$. The pumping power saved is RP_o, where P_o is the power required for $C = 0$. Thus

$$\text{A. E.} = \frac{RL(P_o/L)}{CQ} = \frac{RL}{C} \times \text{const}$$

where P_o/L is the pumping power per unit length for $C = 0$. Thus if polymer degradation is negligible, A. E. will increase indefinitely with L.

For boundary-layer flow, it can be assumed for a first approximation that the local percent skin-friction reduction will require about the same mean concentration across the turbulent boundary-layer thickness, δ, as in pipe flow for $\delta = D/2$ and freestream speed $U_\infty = U$. The friction-reduction factor, R, will be assumed to be determined by C as in the typical pipe-flow results given earlier.

Because the additive concentration in the turbulent boundary layer will be continually reduced by mixing as the boundary layer thickens, more additive will have to be injected at intervals along the plate length, or the concentration will have to be very large near the leading edge. In either case, the total additive supply rate per unit width will be $C(\delta - \delta^*)U_\infty$, where δ^* is the boundary-layer displacement thickness. If θ_o is the momentum thickness for $C = 0$, then the thrust power saved per unit width is

$$R\theta_o(\rho/2)U_\infty^3$$

Thus for a flat plate

$$\text{A. E.} = \frac{R\theta_o(\rho/2)U_\infty^3}{C(\delta - \delta^*)U_\infty}$$

For high Reynolds numbers, reasonable approximations are

$$\delta - \delta^* = k\delta = k'\theta$$

where k and k' are constants as L is varied. Thus

$$\text{A. E.} = \frac{R\theta_o}{C\theta} \times \text{const}$$

and since $\theta/\theta_o = 1 - R$,

$$\text{A. E.} = \frac{R}{C(1 - R)} \times \text{const}$$

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Thus in boundary-layer applications, the additive effectiveness is helped by the reduced boundary-layer throughput as R is increased, but the increase with L is lost.

Since a concentration of a few wppm is 2 to 3 orders of magnitude smaller than that used in the pipe-line applications, the newly discovered effectiveness at such concentrations now makes the situation more hopeful for boundary-layer applications. (Fortunately, for such applications, the extreme sensitivity of the same polymers to mechanical degradation may not be a major problem since the use-time of the polymer is short.) However, calculations indicate that even the increase in the factor 1/C by about 1,000 still leaves the technique of reducing ship friction by boundary-layer additives economically uncompetitive.

Hence until additive costs can be brought considerably lower, this method of drag reduction appears to be reserved for applications where an emergency speed increase would be required. Of course, in an application where a large proportion of the total drag is frictional, such as a slow-speed ship, the technique may look economical.

In any event, the applications of the rather basic experiments presented here are difficult to foresee. Certainly the possibilities of achieving substantial drag reductions with relatively small amounts of additive are attractive enough to warrant intensive further effort.

CONCLUSIONS

From an experimental study of the flow properties of dilute high-polymer aqueous solutions, the following conclusions can be drawn:

1. Many such solutions exhibit marked friction-reduction properties compared with the pure solvent. Drag reductions up to about 80% were measured.

2. The drag-reduction effect is dependent upon Reynolds number, and occurs only in flow situations that would be categorized as turbulent based upon the Reynolds number of the solvent.

3. The three key properties that characterize polymers having drag-reduction effectiveness are linearity, high molecular weight, and solubility.

4. The most effective polymer studied was poly(ethylene oxide), which gave drag reductions of more than 40% at 2 weight parts per million concentration in pipe flow, and more than 75% at 100 wppm.

5. Rheological studies indicate that the viscosity of polymer solutions that are effective from the drag-reduction standpoint is not shear-rate dependent.

6. A theoretical model of the basis for the observed turbulent friction reduction is not available.

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Fig. 1, LHL-P 24277; Fig. 2, LHL-P 24459-5; Fig. 3, LHL-P 24459-7; Fig. 4, LHL-P 24399-3 and LHL-P 25345; Fig. 5, LHL-P 25380-7; Fig. 6, LHL-P 25380-1; Fig. 7, LHL-P 25380-5; Fig. 8, LHL-P 25380-2; Fig. 9, LHL-P 24459-15; Fig. 10, LHL-P 25380-13; Fig. 11, LHL-P 25380-3; Fig. 12, LHL-P 25380-4; Fig. 13, LHL-P 25380-8; Fig. 14, none; Fig. 15, LHL-P 25380-12; Fig. 16, LHL-P 25380-9; Fig. 17, LHL-P 25380-10; Fig. 18, LHL-P 25380-6; Fig. 19, LHL-P 25380-11; Fig. 20, LHL-P 24404-14; Fig. 21, LHL-P 24404-13.

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ABSTRACT. A brief review is given of the literature on turbulent flow of high-polymer solutions. Laboratory experiments using rotating disks and turbulent pipe flow have led to generalizations as to characteristics of friction-reducing high polymers. Linear, high-molecular-weight, soluble polymers are shown to be most effective. The maximum drag reduction achievable by polymer addition appears to be a function of the Reynolds number of the flow.

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